THERMAL TESTS OF 6 KA HTS CURRENT LEADS FOR THE TEVATRON

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ABSTRACT

Prototype current leads incorporating High Temperature Superconductor (HTS) elements have been tested at Fermilab. Fermilab's Tevatron includes about 50 pair of 5 to 6 kA current leads, and Fermilab is investigating the feasibility of replacing some of these conventional leads with HTS leads. The prototype HTS current leads are cooled primarily by a countercurrent flow of liquid nitrogen from the 80 K intercept to the warm end of the leads. Measurement results for heat loads to the 80 K and 4 K temperature levels are presented.

INTRODUCTION

Conventional power leads carry electric current from room temperature to the superconducting magnets in the Tevatron at Fermi National Accelerator Laboratory. Over 50 pair of leads carry up to 6000 amps of current and result in substantial heat loads for the cryogenic system. Reducing the total heat load to the liquid helium temperature level would allow either savings in operational costs or make more refrigeration available for lower temperature and higher energy operation of the Tevatron. Using a combined liquid nitrogen and liquid helium cooled power lead design, one can reduce the heat load to LHe by a factor of ten. A proposal to replace most of the conventional power leads at Fermilab with more efficient HTS leads is under consideration. As a first step toward realizing this plan, American Superconductor Corporation and Intermagnetics General Corporation each developed and built a pair of 5000A HTS current leads. These leads went through extensive tests at Fermilab. The focus of this paper is on the thermal studies.

(Some example footnotes.[1,2])

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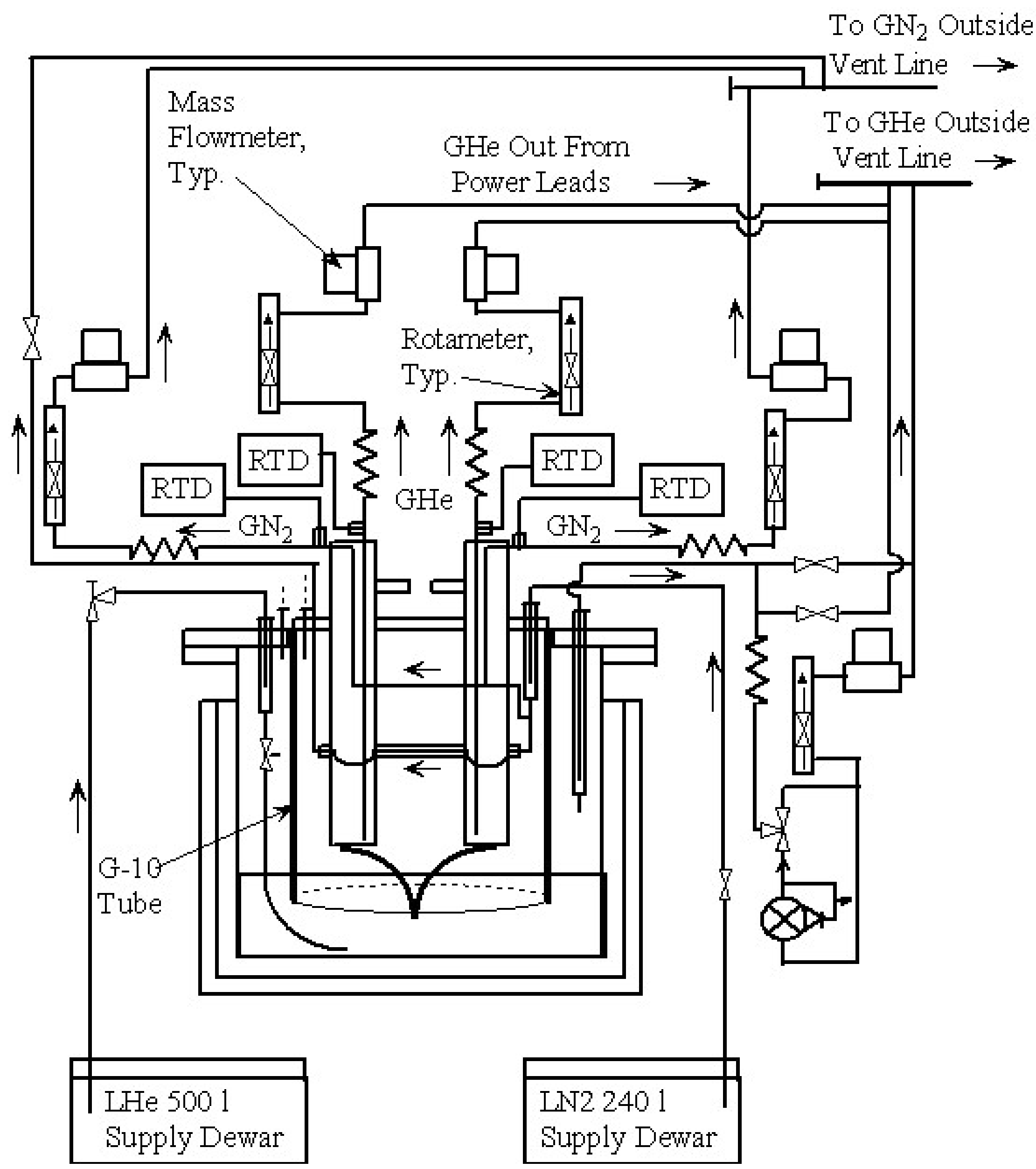


Figure 1. The current lead test schematic.

TEST APPARATUS

The HTS power lead testing equipment is located in the Magnet Test Facility (MTF) at Fermilab. The mechanical system consists of a liquid nitrogen shielded helium cryostat with a baffle system that includes an 80 K intercept, and the instrumentation necessary to monitor mass flow rates, measure and regulate system pressures and liquid level, and record system temperatures. The 20 inch diameter by 42 inch long helium vessel is sized to accommodate power lead pairs, which are spaced on a 4 inch center-to-center distance, and are up to 30 inches long. The leads are mounted on a plate that is separate from the main vessel cover plate. This feature allows for power lead removal without complete disassembly of the vessel cover plate. The remaining top surface area of the vessel accommodates fill and vent lines, valves, liquid level sensors, and other instrumentation.

To thermally separate the main dewar volume from the volume immediately around the power leads, the leads are housed inside a glass/epoxy tube that extends from the cover plate to several inches below the minimum liquid helium level in the main dewar. To further thermally isolate the two volumes, the power lead pair and glass tube assembly is mounted inside a vacuum jacketed sleeve, that extends to the depth of the liquid nitrogen cooled intercept. Anticipating differences in pressure due to the different thermal environment in each, the system provides for independent or simultaneous venting of the two volumes. A backpressure regulator, sensitive to 1/8 inch of H_2O pressure changes was installed to help maintain a constant pressure in the main bath, while pressure changes may be occurring inside the glass/epoxy tube.

The mass flow meters and rotameters used in the system were carefully calibrated and sized to operate effectively over the range of flows required. The HTS data acquisition (DAQ), and the quench detection and management systems used in this test are adapted and extended from those systems developed at MTF to conduct tests on superconducting R&D magnets. Temperature and voltage measurements from the DAQ scans are monitored by a new software quench detection system that triggers the quench management system to protect the leads from (relatively slow) quenches. An independent hardware backup system protects against ground faults as well as fast resistive voltage growth across the leads. A quench is detected when one of the analog signals or software process variables exceeds a (configurable) threshold, or when a scan malfunctions. When triggered, the management system initiates fast quench data logging, and slow power supply ramp down.

The quench thresholds were set low, for any temperature rise of 5K above the zero-current baseline temperature profile, or HTS (Copper) voltage (imbalance) greater than one(32) millivolt(s). Temperature and voltage process variables were monitored and logged by two independent scan systems, which used complementary instrumentation schemes. The carefully wired and isolated sensors delivered typical noise levels of less than 1K for temperatures, and less than 3~μV for voltage taps at 5000A.

(At the end of the next sentence is another example footnote. This heat exchanger is similar to the analogous one in our horizontal superfluid test stand (Stand 5)[3].)

THERMAL TEST.

After the HTS current lead ability to operate under even 7500 Amp was demonstrated the main task became to determine experimentally the heat inflow through the copper section to the interception stage cooled by LN2 and heat inflow to LHe through the HTS section. The thermal tests were done for conduction mode, while HTS section was cooled by only heat conduction from 80 K to 4.5 K; self-sufficient mode, while all boil-off helium inside the cup was used for cooling the leads; and regular mode, while He cooling flow through the leads was adjusted to be 0.006, 0.011 and 0.025 g/sec. During the thermal tests we try to maintain all parameters constant (pressure, LHe level inside the cup, He gas flow through the current leads, LN2 flow to interception stage).

To determine heat inflow (heat input, heat leakage ???) to the interception stage the LN2 cooling flow was being reduced stepwise until the temperature of the outgoing nitrogen started to rise (raise). It meant that all LN2 supplied to cool the interception stage was boiled-off. He cooling flow through inside the lead was maintained as recommended by vendor: **0.026 g/sec** without current and **0.033 g/sec** with 5 kA. It was found that the minimum required LN2 flow without current was **0.24 g/sec** and **0.53 g/sec** at 5 kA, that correspond the heat inflows to the interception stage **46 Watt** and **101 Watt**, respectively**.**

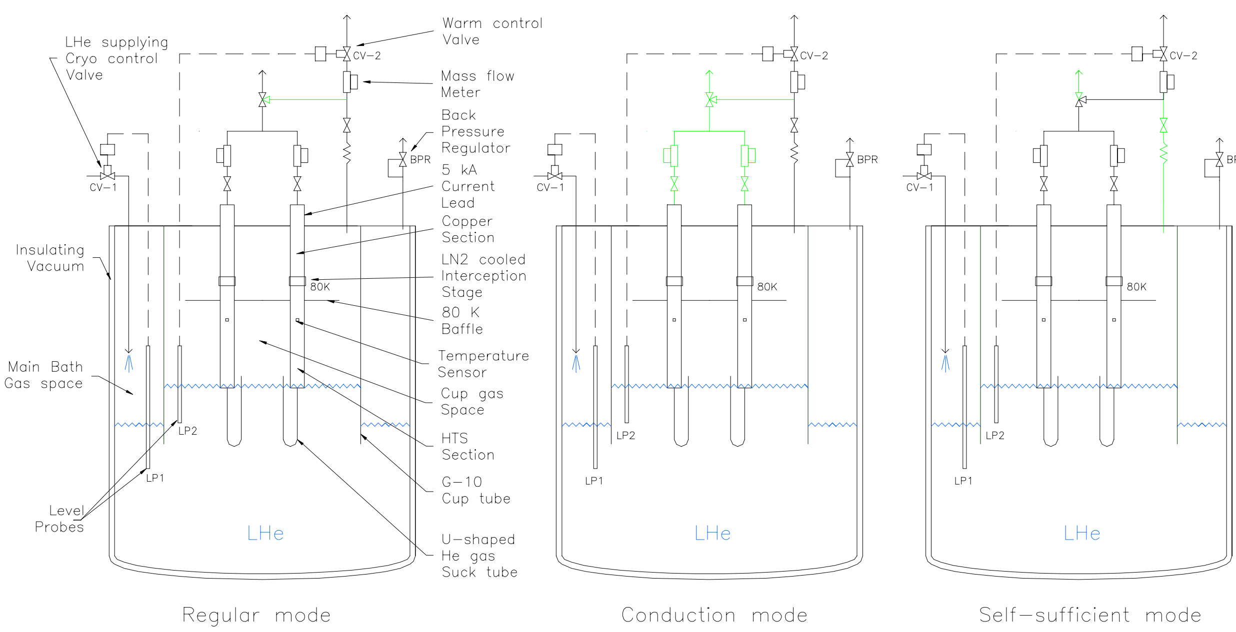


Figure 2. The different modes of cooling. Thin line means that this line is not active at the mode.

The first attempts to measure the heat inflows to the LHe were not successful, for it was not managed to maintain constant pressure and LHe level inside the cup. Liquid helium is 8 times lighter than water, therefore even tiny change of differential pressure between cup and MB volumes results in huge cup level change. For example, only 1 Pa differential pressure causes cup LHe level change on 1 mm. To maintain constant pressure and LHe levels in MB and cup volumes some automation was implemented (Figure). Cryogenic control valve CV-1, which regulates LHe flow through transfer line from supply dewar, is controlled by signal from 0.76 m length level probe installed in MB. If MB level drops below set point then CV-1 is opened to supply more LHe to keep the MB level constant. Warm control valve CV-2 is controlled by signal from 0.32 m length level probe installed in cup. If cup LHe level is elevated above set point the CV-2 is closed to build up Cup pressure to push liquid down to the set point; and vise versa. To maintain constant pressure inside MB of the test dewar a back pressure regulator sensitive to 320 Pa (1/8 inches of H_2O) pressure changes was installed. To provide necessary throughput through CV-2 control valve and through the back pressure regulator the pressure inside MB was hold 0.13 MPa (19 psia). This automation being implemented allowed maintaining the pressure within 200 Pa (0.03 psi), MB LHe level within 1 mm and Cup LHe level within 0.4 mm for hours during test.

First test LHe boil-off measurements.

Measurements of the heat inflow through the current leads into LHe were done under conduction, regular and self-sufficient modes. For each mode its unique schematic was used. At conduction mode no He cooling flow was allowed. All **boiled off** helium went out of the cup volume through a hole in the top plate and then through mass flow meter (**Figure 2**). At regular mode He cooling flow through the leads was setup at different rates, while the rest cup boil-off helium went out through a hole in the top plate and was measured by mass flow meter. At self-sufficient mode all cup boil-off helium went out through inside the leads and was measured by the mass flow meters.
The results of the boil-off rate measurements shown on **Figure 3.** One can see that at conduction mode the measured boil-off rate was around 0.05 g/sec per lead with no current and 0.058 g/sec with current 5-6 kA, what corresponds, respectively, to the heat inflow into LHe at pressure 0.13 MPa (19 psia) 0.92 W and 1.07 W per lead.

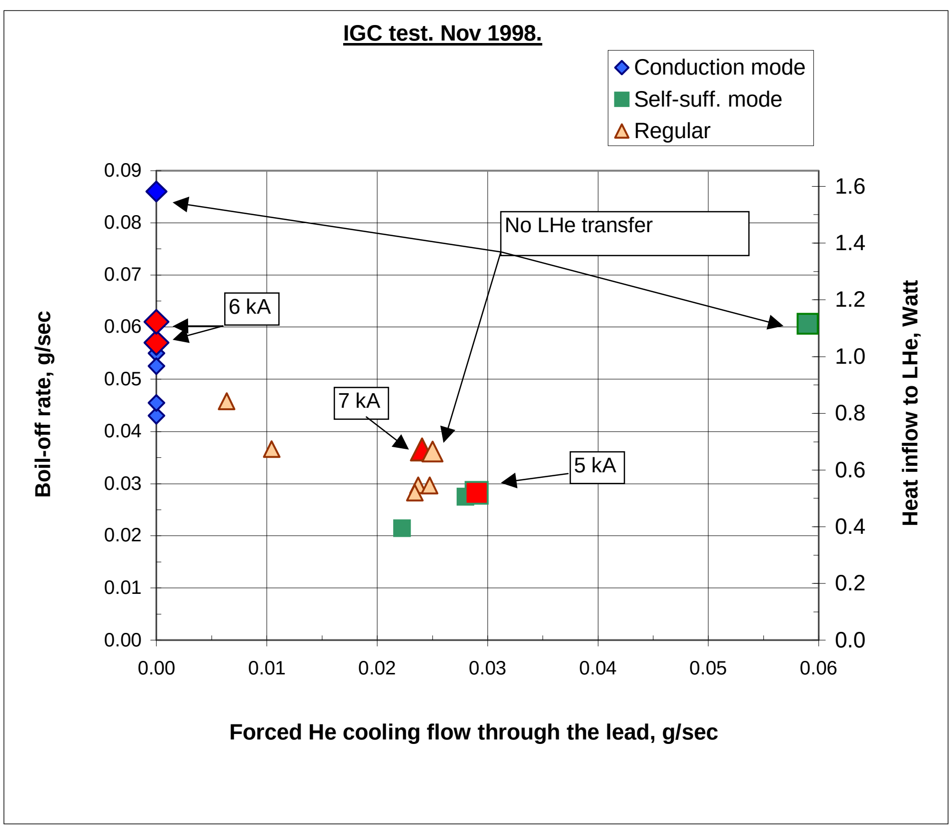


Figure 3. Boil-off rates at conduction mode.

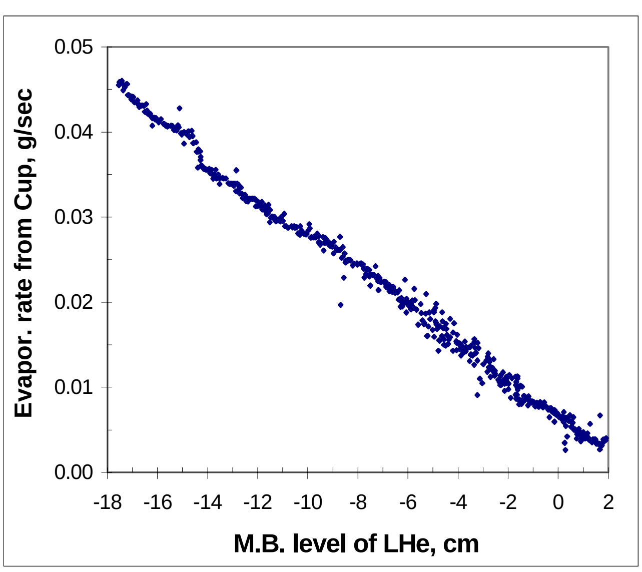
At regular mode the more He boil-off gas was directed to cool the lead, the less heat inflow into LHe was: 0.81 W (0.044 g/s of boil-off rate) per a lead with cooling flow through a lead 0.006 g/s; 0.64 W (0.035 g/s) per a lead with 0.01 g/s through a lead; and 0.53 W (0.029 g/s) with no current and 0.68 W (0.037 g/s) at 7 kA with 0.024 g/s through a lead. This forced He cooling flow through a lead 0.024 g/s was the maximum one, which one managed to provide with the existing pressure inside dewar 0.13 MPa.

At self-sufficient mode the LHe boil-off rate was measured 0.022-0.028 g/s (0.4-0.52 W) per a lead at zero current and 0.029 g/s (0.53 W) at 5kA.
During the first test the boil-off rate measurements were done both when LHe was added to maintain constant MB level and when MB level dropped slowly, since no LHe was transferred. It was noticed that at each of these three modes the boil-off rate was higher while no LHe transferring was carried out. Another strange thing was that no LHe transferring the boil-off rate at self-sufficient mode was much more than at regular mode and even more than at conduction mode, but when LHe does was transferred into MB. One can see on **Figure 3** that when no LHe was transferred into MB the LHe boil-off at conduction mode was 0.086 g/s (1.6 W) per a lead; 0.035 g/s (0.64 W) per a lead with 0.025 g/s forced He cooling flow through a lead at regular mode; and 0.059g/s (0.92 W) at self-sufficient mode.
An explanation suggested consisted in an assumption that temperature in the MB gas space is lower due to good convection caused by LHe transferring and it results in permanent heat flow from cup gas space through the G-10 cup tube into the MB gas space. Thus, the colder gas around the cup G-10 tube works like a heat pump cooling down gas inside the cup and reducing the real LHe boil-off rate inside the cup. When no LHe is transferred no forced convection in MB gas space there is, and temperature distribution by the height in MB gas space is closer to the one in cup gas space.

<u>Background boil-off measurements without LHe transferring.</u>

5. **Measurements of Background boil-off without LHe transfer. (Figure: LHe boil-off rate vs. MB LHe level).**

All boil-off rates given above include background LHe boil-off which occurs even without current leads due to the usual heat leakage mechanisms: radiation and conduction through thermal bridges. To determine this background boil-off a test without current leads was carried out. To have more quiet **(calm)** thermal conditions during test LHe transfer was stopped and the boil-off measurements were done while MB LHe level was dropped slowly, but cup level was hold constant.



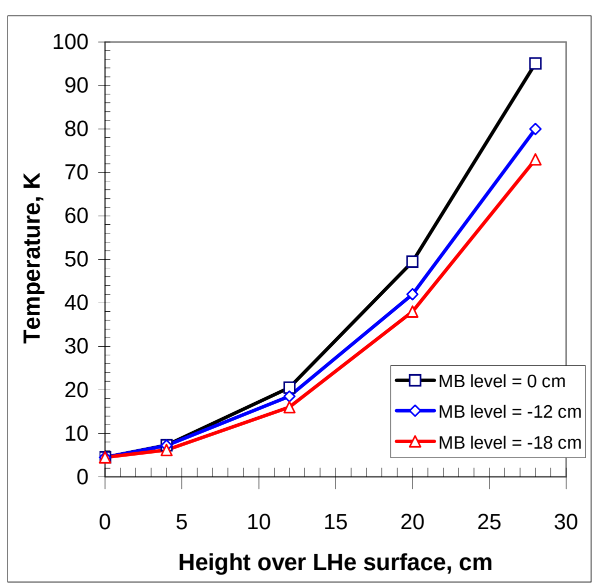
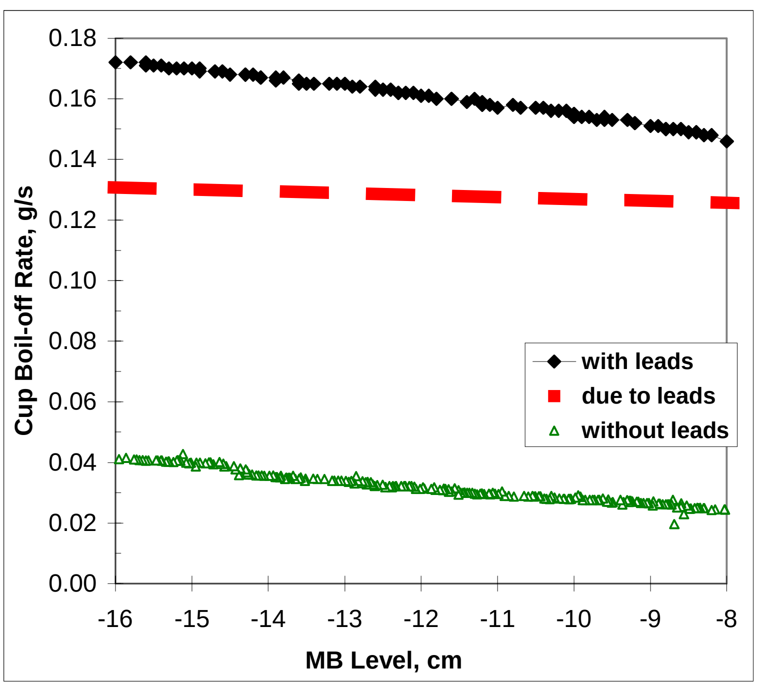


Figure 4. 2 Apr99; Background boil-off rate from Cup vs. M.B. level (No LHe transfer).
Figure 5. Temperature distribution in Cup space. 2 Apr 99 (No leads)

The results of the test is show on **Figure 4.** It turned out that the background boil-off rate depends on MB level. The background boil-off rate was 0.003 g/s (0.057 W) when MB level was 1 cm higher than cup level; 0.05 g/s (0.095 W) while LHe level inside and outside the cup was the same; and 0.045 g/s (0.86 W) while MB level was 18 cm lower than the cup level. Temperature distribution inside cup gas space measured during the test is shown on **Figure 5**. One can expect that temperature distribution inside MB gas space was similar, since **(for)** there was no forced convection in MB gas space. It means that the lower LHe level was in MB, the more temperature difference was at the same elevations across the G-10 cup wall and, consequently, the more heat was transferred into cup region, increasing the background boil-off rate. One can see on **Figure 5** that the temperature profile in the cup gas space (which apparently follows the one in MB gas space) is rising while level in MB dropping.

6. **Subtraction of the Background boil-off values from the boil-off rate measured with current leads (Figure: Boil-off rates with & without leads vs. level in MB and horizontal curve obtained after subtraction)**

More measurements of cup LHe boil-off were done when no LHe was transferred and MB level was dropping. On **Figure 6** is shown one of the typical boil-off curves obtained at conduction mode. One can see that the boil-off rate is not constant and is changed from 0.145 up to 0.172 g/s while MB level dropped from 9 cm down to 17 cm below the level in the cup. However, after subtraction the background boil-off at the adequate **(corresponding)**



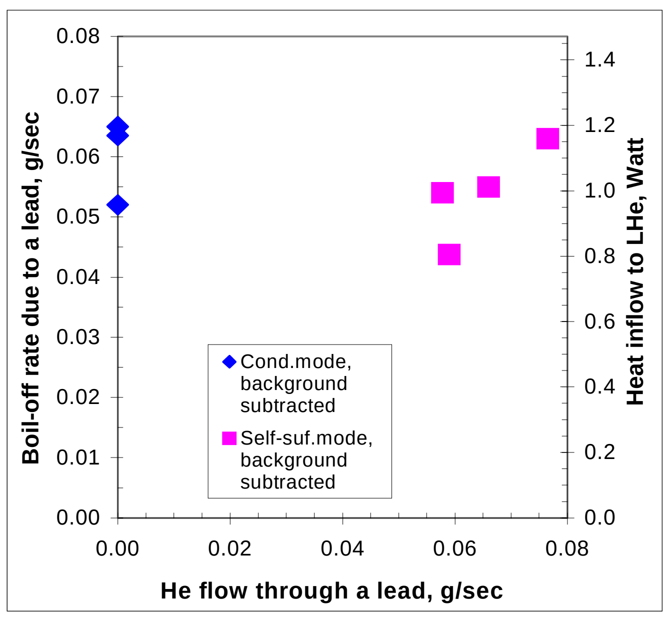


Figure 6. Cup Boil-off Rate with & without Leads vs. Level in MB. 23 March (with) & 2 Apr (without leads) 1999.

Figure 7. LHe Boil-off Rate due to a Lead (background ev. rate subtracted) 23 & 24 March 99. IGC test.

MB levels it becomes clear **(apparent)** that with constant cup level the boil-off rate due to leads only is a constant value. The results of the boil-off measurements at conduction and self-sufficient modes after background subtraction are shown on **Figure 7**.

Unexpectable result was that boil-off rate at conduction mode is approximately the same as at self-sufficient mode. The reason of this consists in different thermal conditions around the current leads at conduction and self-sufficient modes. At self-sufficient mode all boiled-off gas is sucked into the leads through the U-shaped tubes with the temperature a little bit higher than liquid one, since the edge of the U-tube is 4 cm over the LHe surface **(Figure 2).** Passing through the copper U-tubes immersed in LHe like through the heat exchanger the warm gas increases the cup LHe boil-off rate in comparison with the conduction mode, when there is no he gas flow through the U-tubes. On the other hand at conduction mode with no cooling gas through inside a lead the temperature of the lead is much higher than the temperature of the surrounding He. G-10 lead shroud appeared not to be a good insulator and actually some lateral cooling of the lead occurs, which reduce the heat inflow into liquid He. Besides, in distinguish from the self-sufficient mode when He is stuck in cup gas space, at conduction mode all boiled-off He is vented out through the hole in the top plate. Thus there is a motion of gas up, what increases the lateral cooling, reducing LHe boil-off rate down to the values at self-sufficient mode.

7. Modernizing test stand: Vacuum-jacket U-shaped tube, location of temperature sensors & 2 watt Heater. (Figure of test dewar).

After understanding of the crucial role of convection and that 3 mm G-10 lead shroud and cup wall are nearly transparent for the heat flows it was decided to modernize test stand in the following way **(Figure 8)**.

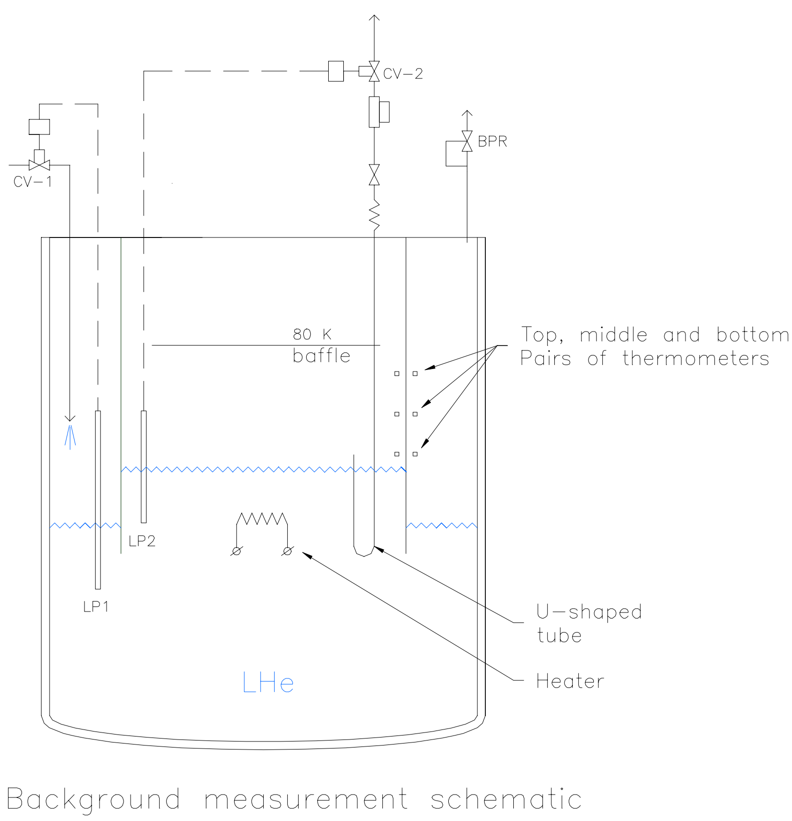


Figure 8.

To make the background boil-off measurements more prototypical, we inserted U-tube to evacuate the evaporated inside the cup He in the similar way like with the current leads at self-sufficient mode; to measure temperature profiles three pairs of thermometers were installed on the same elevations inside and outside cup. The vertical distance between the pairs is 9.2 cm. The lowest pairs of sensors are on the elevation of the U-tube edge to know the temperature of sucked gas. The highest sensors are on the elevation of a thermometer embedded in the middle of HTS section to know the temperature difference between the lead and surrounding gas. In order to understand gas flow influence inside the cup on boil-off measurements an electrical heater was installed to simulate heat inflow to LHe, which occurs with current leads.

8. **Measurements of Cup Background LHe Boil-off during LHe transferring into the MB under different Heater Powers and MB LHe levels. (Curve: LHe boil-off vs. Heat Inflow into LHe (Heater Power)).**

This time the background boil-off measurements were done while LHe was transferred into MB to maintain a constant MB level. The power dissipated on the heater was changed stepwise from 2 Watt, down to 1.16 W, 0.5 W, 0.13 W and 0 W by applying current, respectively, 0.1 A, 0.075A, 0.05 A, 0.025 A and 0 A. The resistance of the heater measured at 293 K and at 4.5 K was 200 Ohm and 202 Ohm, respectively. The dependence of the LHe boil-off rate vs. dissipated in LHe power is shown on **Figure 9.** The measurements were

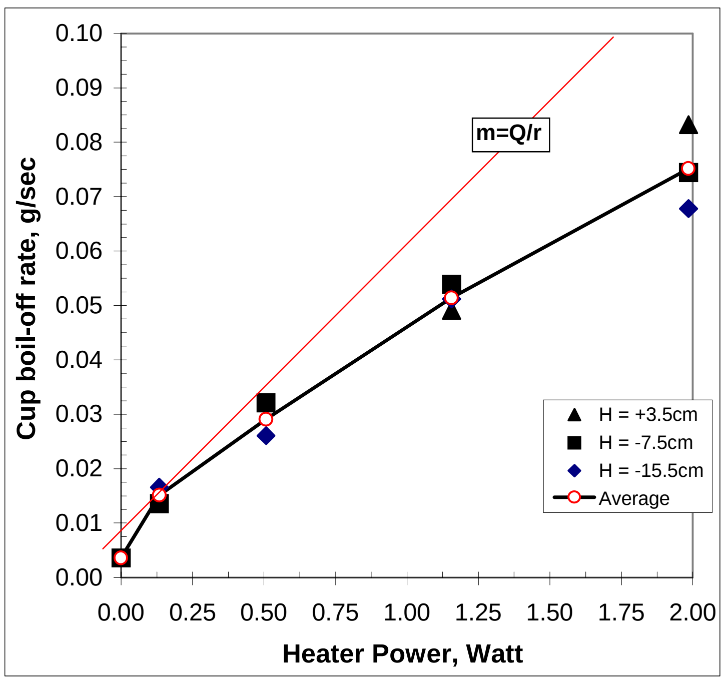


Figure 9. Cup Boil-off Rate vs. Heater Power under different LHe levels. 16 June 99.(No leads; LHe transfer).

done at the different LHe levels in MB: +3.5 cm, -7.5 cm and -15.5 cm relatively to a cup level, which was always maintained the same. No correlation of boil-off rate with MB level was noticed. Knowing the dependence of measured flow from the cup on the heat inflow into LHe obtained without current leads, one can find what was the actual heat inflow through the leads only (without background heat leakage). The total measured boil-off rate at self-sufficient mode (while LHe was transferred) was 0.052 g/s at zero current and 0.058 g/s at 5 kA. Looking at **Figure 9** one can see that it corresponds to the heat inflow through the leads 1.2 W and 1.4 W, respectively; or per a lead 0.6 W with no current and 0.7 W at 5 kA. The boil-off rates are underestimated, since in reality there was additional lateral cooling of the leads through G-10 shroud by the surrounding gas.

It was expected that the dependence of LHe boil-off on the dissipated heater power should be linear (m=Q/r) starting from a background value at 0 Watt. However, the amount of increase in measured mass flow from the cup was less than that corresponding to the additional heat from the heater. The difference is considered to be the result of an extra cooling of the cup gas through the G-10 cup wall. For both cup and MB levels were maintained to be constant the increasing by heater LHe evaporation had to be compensated by adding more LHe into MB. Actually, the flow going out of the transfer line is a liquid-vapor mixture with bigger percentage of saturated vapor in it. LHe transfer increasing means much more cold gas supplying, The increased cold gas flow up along the G-10 cup tube, while no forced motion in cup gas space, results in better heat transfer through the G-10 cup wall and extra cooling of cup gas. Because of background heat leakage we always have to transfer LHe even with zero heater power. Thus, the “cryo pump” heat flow (or “negative boil-off”) always exists. It can be found as a subtraction of the m=Q/r line from the

experimental “boil-off curve”. The value of the “cryo pump” heat flow appeared to be more than the background cup heat inflow to LHe. It explains the “crazy” situation when with zero heater power the cup level began rising while the CV-2 vent valve was completely closed and no gas vented out of the cup gas space. The cup level rising caused by the “cryo-pumping” resulted in MB level dropping. To compensate it the control valve CV-1 opened more supplying more liquid-vapor mixture, what increased the “cryo-pumping” more. This positive feedback resulted in runaway situation, complete stability loss of levels, pressure and temperatures. To overcome the problem we began measurements from maximum power 2 W and reduced it stepwise down to 0 W. We repeated the measurements three times (with different level in MB), but managed to measure the background boil-off rate with zero heater power only once. At two other attempts the run-away situation was developing.
An explanation of the abrupt banding down **(downturn, kink)** of the curve when the heater power becomes below 0.13 W is the following: evaporation of LHe by the heater creates some convection inside cup gas space mixing up colder gas from lower gas layers with warmer higher gas layers. This decreases an average temperature in cup gas space and, consequently, reduces the “cryo-pump” heat flow. At definite conditions the “cryo-pump” heat flow might be zero, or even change the sign. However, when the heater power is low the evaporation of LHe is not enough to create good convection and mix up gas inside the cup. This results in increasing the “cryo-pump” heat flow, and as a consequence in the abrupt decreasing of the measured cup boil-off rate.

9. Temperature distribution in MB and Cup gas spaces during LHe transfer. Temperature distribution in Cup gas space while MB LHe level drops (No LHe transfer). Temperature rise (raise) in MB and Cup after LHe transfer interruption.

Temperature distribution in MB and Cup gas spaces with different levels in MB during LHe transfer is shown on **Figure 10**. One can see that because of very good convection in MB

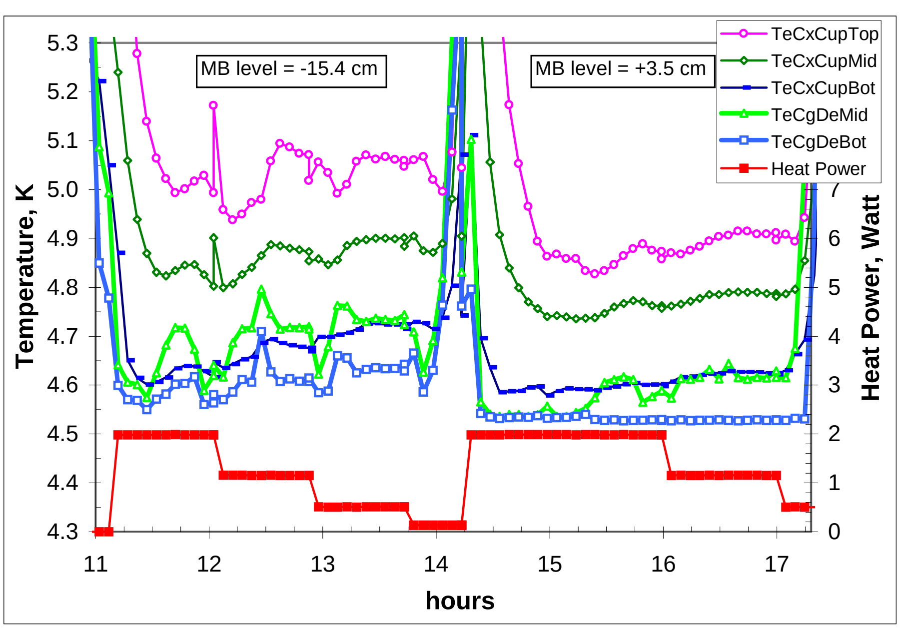


Figure 10. Heater Power & Temper. distribution in MB & Cup spaces vs. time. 16 June99.

during LHe transferring the temperatures in MB gas space are pretty much the same at different elevations. One surprising thing is that the temperatures inside the cup space are very close to the MB space temperatures. The difference between MB and cup temperatures at the same elevations is only 0.1 – 0.2 K. It means that the temperature profile inside the cup follows the MB temperature profile, as though these two gas spaces are not separated by G-10 cup wall. One can see on **Figure 11** that after the LHe transfer was stopped the temperature changes in both gas spaces absolutely follow each other. The thermometer installed in the top of MB gas space is a platinum thermometer, which loses its sensitivity below 40 K. It again proves that the 3 mm G-10 cup wall is actually transparent for the heat

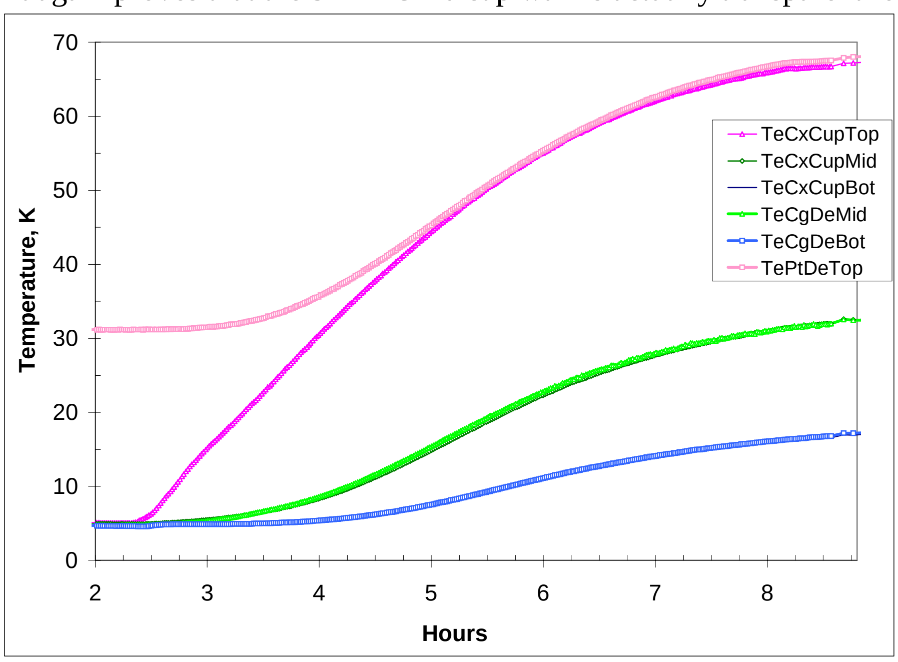


Figure 11. Temperature distribution in MB & Cup spaces vs. time. 16 June99.

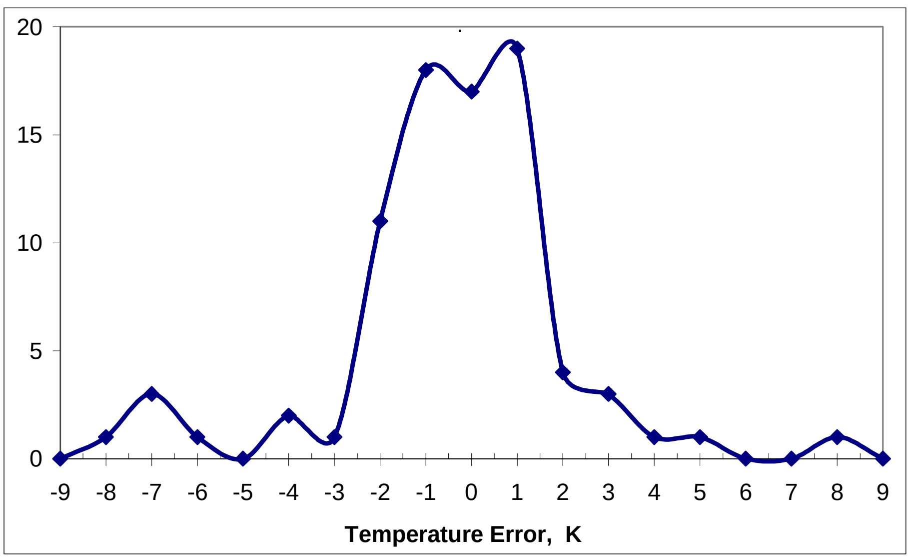
transfer between these MB and cup gas spaces. It is wondering that though there is no forced convection in cup space and gas is stuck the cup temperature profile dramatically depends on LHe transfer mode. The temperature gradient in cup space between top and middle sensors is about 0.001 K/mm while LHe is transferring into MB and 0.38 K/mm with no LHe transfer. The process of temperature stabilization in gas spaces took several hours.

After these temperature distribution measurements and understanding the G-10 wall transparency for heat transfer it is clear that there is no pure conduction mode. Always there exists a good lateral heat transfer through the G-10 shroud. Comparison HTS section temperature with surrounding He temperature shows (proves) that during LHe transfer the surrounding gas cools the HTS section what reduces the measured LHe boil-off rate, but with no LHe transfer the surrounding gas warms the HTS section what increases measured LHe the boil-off rate.

10. Temperature distribution along a lead immersed in LN2. (Figure: Temperature distribution along a lead immersed in LN2 with and without N2 gas cooling flow)

It turned out during the thermocycling tests that, when a lead partly immersed in LN2 while the upper lead flag has room temperature and there is no gas cooling flow inside the lead, there is a huge radial temperature gradient. On **Figure 12** ??? are shown the temperatures of the lead part immersed in LN2. One can see that the temperatures inside the lead are about 200 K, while surrounding LN2 has 77 K.

11. Error readings of the Temperature sensors embedded in the lead apparently associated with a temperature stress (tension).(Error Distribution curve. Gauss distribution)



Temperature sensors inside the leads are not free, but glued by epoxy. It results in a stress on the sensors, which is changed with temperature. The error in the sensor readingout caused by the stress reaches sometimes 15 K. The error distribution is shown on **Figure 13.**

Figure 13.

12. Seeming LHe boil-off rate due to warming gas expansion and math model to estimate this extra flow rate due to He temperature expansion.

TEST RESULTS

DISCUSSION

CONCLUSIONS

The HTS leads work, and Gregory and Sandor are great guys. But don't forget who are the real men: Tommy and Cosmore….

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REFERENCES

1. G. Claudet, et. al., The design and operation of a refrigerator system using superfluid helium, in: "Proceedings of the 5th International Cryogenic Engineering Conference," Kyoto (1974), pp. 265-267.
2. G. Claudet, et. al., Superfluid helium bath for superconducting magnets, in: "Proceedings of the 6th Cryogenic Engineering Conference," Grenoble (1976), pp. 159-162.
3. P. O. Mazur and T. J. Peterson, A cryogenic test stand for full length SSC magnets with superfluid capability, in: "Advances in Cryogenic Engineering," Vol. 35, Plenum Press, New York (1990), pp. 785-792.
4. S. Y. Seol and J. R. Hull, "Transient analysis and burnout of high-temperature superconducting current leads," \QTR{it}{Cryogenics} 33 (1993) 966.
5. G.Citver, E. Barzi, A. Burov, S. Feher, P.J. Limon, T. Peterson, "Steady State and Transient Current Lead Analysis", ASC'98,Palm Desert, CA (1998).
6. G.Citver, S. Feher, P.J. Limon, D. Orris, T. Peterson, C. Sylvester, M.A. Tartaglia, J.C. Tompkins. "HTS Power Lead Test Results", PAC'99, New York City, NY, (1999).
7. R.C. Niemann, Y.S. Cha, and J.R. Hull, Perfomancemeasurements of superconducting current leads with low helium boil-off rates, IEEE Trans. Appl. Superconductivity 3(1):392 (1993).

THE HEAT INFLOW TO LHE THROUGH THE 6 KA CURRENT LEADS. (BOIL-OFF MEASUREMENTS)

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